Reducing Restrained Shrinkage Cracking in Concrete: 
Examining the Behavior of Self-Curing Concrete Made using 
Different Volumes of Saturated Lightweight Aggregate

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ABSTRACT

Increased observations of cracking in bridge decks have spawned innovative developments in the design of materials that reduce the potential for cracking. This study examines one of these technologies: self-curing concrete. Self-curing concrete technology involves the use of saturated lightweight aggregates to provide additional water to counteract the effects of drying and self-desiccation. This study highlights the shrinkage behavior of concrete containing saturated lightweight aggregate with different volume replacements. The results of the study indicate that when a sufficient amount of lightweight aggregate is used, saturated lightweight aggregate is an effective way to reduce shrinkage and delay or prevent cracking.

Keywords: Internal Curing, Autogenous Shrinkage, Lightweight Aggregates, Shrinkage Cracking, Drying Shrinking,
OVERVIEW AND OBJECTIVES

Shrinkage cracking in concrete has become a growing concern in the industry. This concern has spawned the development of several strategies to reduce shrinkage in concrete, such as changes in design and construction practices, the incorporation of shrinkage reducing admixtures\(^1\), using expansive cements\(^2\) and the inclusion of saturated lightweight aggregates (LWA)\(^3, 4\). The latter strategy, known as self-curing concrete is the primary focus of this paper.

Several studies have shown the beneficial effects of entrained water (i.e., self-curing) on the early-age shrinkage behavior of low water to cement ratio mixtures\(^5, 6\). The majority of work has focused on understanding the behavior of sealed systems, however little is known about drying shrinkage\(^7\). This study provides data which can be used to better understand the behavior of the mixtures when different volumes of LWA are used and the behavior of these mixtures when they are exposed to a drying environment.

The objectives of this paper are:

- To discuss the difference between sealed and unsealed curing conditions and the implications on the shrinkage behavior of concrete containing LWA.
- To provide experimental measurement of shrinkage performance of a plain low w/c mortar and several mortars with varying LWA volume replacements. These experimental measurements include drying shrinkage, autogenous shrinkage, restrained shrinkage and internal relative humidity.

While this technology shows great potential, mixture proportioning must be carefully considered in order to take full advantage of self-curing concrete\(^8\). This paper provides data that can be used in determining how mixtures can be proportioned to produce self-curing concrete.

THEORETICAL CAUSE FOR SELF-DESICCATION

Low w/c mixtures undergo self-desiccation, even if they are sealed. Self-desiccation occurs as a result of chemical shrinkage. Chemical shrinkage is the natural process that occurs during the hydration process where the hydration products occupy a smaller volume than the reactants\(^9\). Before the concrete sets, chemical shrinkage causes the concrete to collapse upon itself resulting in a reduction in volume that is equal to the amount of autogenous shrinkage. After the concrete has set however, concrete can no longer collapse upon itself and voids are created. The voids are filled with water vapor\(^10\) as illustrated in Figure 1a. As water is consumed by hydration, these voids expand resulting in a reduction in internal relative humidity and effects that are similar to internal drying. Conceptually the process of self-desiccation is shown in Figure 1a. This ‘internal drying’ is conceptually different from ‘external drying’, which is shown in Figure 1b. When concrete dries from the environment, menisci form near the surface. It should be noted that Figure 1b is a hypothetical case as
external drying in a low w/c concrete experiences both surface menisci and internal vapor filled voids as shown in Figure 1c.

Figure 1 Illustration of drying mechanisms in sealed and unsealed systems: (a) Sealed – only internal drying, (b) Only external drying, (c) Unsealed – internal plus external drying

Lightweight aggregate can be used to supply water during the curing process to mitigate the effects of self-desiccation in low w/c concrete mixtures. The basic principle of using LWA is that the largest pores lose water first. The idea in using LWA is that it acts as a water reservoir that can provide water to replenish the water that is consumed by hydration. This is illustrated in Figure 2. As previously mentioned, the largest pores will empty first. In a sealed system, pores smaller than a specific size ($r_1$) will remain saturated. In a LWA system, the emptying pores can be replenished from water in the LWA, provided the water is stored in a larger pore ($r_2$). It should be noted that Figure 2 is for conceptual purposes and that the pores of the LWA may eventually empty, depending on the extent of self-desiccation. In the unsealed system, this becomes more complicated, since the system will come to equilibrium to the ambient relative humidity resulting in an equal pore radius ($r_3$). The presence of the LWA may result in a reduction in the rate of shrinkage or a reduction in the overall shrinkage due to continued hydration.

Figure 3 illustrates the most salient feature of LWA, a desorption isotherm (i.e. the mass of the water that is lost at different humidities). It can be seen a majority of water is lost at a high relative humidity (RH>96%) implying the pores are larger than those in the cement paste, and the water is available at high relative humidities.
Figure 2 Conceptual illustration of the menisci formation in sealed and unsealed specimens made of plain and LWA concrete illustrating that larger pores empty first.3

Figure 3 Desorption characteristic of light-weight aggregate.

EXPERIMENTAL MEASUREMENTS

MIXTURE PROPORTIONING

Four different mixtures were prepared with an effective water to cement (w/c) of 0.30: this included a plain mortar mixture designated as plain and three mortar mixtures with varying volumes of sand replaced by saturated LWA designated as 7.3%, 14.3% and 25.3%. The designation represents the percent of the total volume of the mixture occupied by the LWA. It is important to note that though the designations are on a total volume basis, the volume of aggregate (LWA and sand) remained constant at 55% since only the sand was replaced with...
LWA. It should be noted the 25.3% volume replacement corresponds to the volume necessary to eliminate self-desiccation proposed by Bentz. The mixture proportions for each mixture can be found in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Plain</th>
<th>7.3%</th>
<th>14.3%</th>
<th>25.3%</th>
</tr>
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<tr>
<td>Cement</td>
<td>1228</td>
<td>1228</td>
<td>1228</td>
<td>1228</td>
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<tr>
<td>Water</td>
<td>368</td>
<td>368</td>
<td>368</td>
<td>368</td>
</tr>
<tr>
<td>Fine Aggregate</td>
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<td>2072</td>
<td>1755</td>
<td>1360</td>
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<tr>
<td>LWA</td>
<td>0</td>
<td>192</td>
<td>384</td>
<td>624</td>
</tr>
<tr>
<td>Additional Water Provided by LWA</td>
<td>0</td>
<td>20</td>
<td>40</td>
<td>66</td>
</tr>
</tbody>
</table>

CONSTITUENT MATERIALS

ASTM C150 Type I ordinary portland cement (OPC) was used, with a Blaine fineness of 370 m²/kg, a Bogue phase composition of 56% C₃S, 16% C₂S, 12% C₃A, 7% C₄AF and a Na₂O equivalent of 0.68%.

A high-range water-reducing admixture (HRWRA) was added in varying rates depending on the volume replacement of LWA. For a replacement volume of 7.3% the HRWRA was added at a rate of 6.3 fl. oz. per 100 lbs of cement. For a replacement volume of 14.3%, the HRWRA was added at a rate of 7.2 fl. oz. per 100 lbs of cement. For a replacement volume of 25.3% 9.4 fl. oz. of the HRWRA per 100 lbs of cement was used. Different rates of water reducer were used to keep similar consistencies of these mixtures.

The sand used was natural river sand with a fineness modulus of 3.13.

Portions of the sand were replaced with manufactured rotary kilned expanded shale (Solite) with a fineness modulus of 3.10. The 24 hour absorption of the LWA was determined to be 10.5% according to ASTM C128-07.

MIXING PROCEDURE

The mixing procedure used was in accordance with ASTM C192-06. The LWA was oven dried, air cooled, and then submerged in water for 24±1 hours before mixing. The volume of water used to submerge the LWA included both mixing water and the water the LWA would absorb in 24 hours. The excess water (water not absorbed in 24 hours) was then decanted and used as the mixing water. The sand was oven dried and subsequently cooled before incorporation into the mixture.
EXPERIMENTAL PROCEDURES

Measurements of Volumetric Change during the First 24 Hours

The autogenous deformation of all the mortar specimens can be measured during the first 24 hours using the corrugated tube procedure\(^{13, 14}\). This procedure involves placing fresh mortar (approximately 15 minutes after water is added to the mixture) in a corrugated polyethylene tube. The length-to-diameter ratio of the tube was 16 in to 1.2 in. The tube has a higher stiffness in the radial direction than the longitudinal direction. The volumetric changes are transformed into linear changes measured with LVDT transducers. For every mixture unrestrained volumetric change after 24 hours was measured, two corresponding corrugated tubes were measured. The specimens were placed in a dilatometer which was maintained at 23.0±1.0°C. The transducers were connected to a PC for automated length measurements every 5 minutes for the first seven days.

Measurements of Unrestrained Volumetric Change after 24 Hours

Free shrinkage was measured using 3×3×11.25 in prisms according to ASTM C157-04 with a slight modification on the area exposed to drying. Three samples were prepared from each mixture for both sealed and unsealed conditions. The sealed samples were covered with aluminum tape on all sides. All the sides of the unsealed samples were covered with aluminum tape except two diametrically opposed sides (3×11.25 in). The samples were exposed to a relative humidity of 50%±2.0%. The length change was measured using a comparator beginning 24 hours after casting. The mass loss was recorded for both sealed and unsealed conditions. The mass loss for the sealed samples was measured to ensure a sealed state was maintained during testing. The mass loss measurements for the unsealed samples can be used to monitor the extent of drying (water loss) that has occurred.

Restrained Shrinkage Measurements

The cracking potential was measured using the restrained ring test, in accordance with ASTM C1581-04. Three samples of each mixture were measured for both sealed and unsealed conditions. Before casting, molds were conditioned in an environmental chamber at a temperature of 23.0±1.0°C. Each ring was cast in two layers with each layer being vibrated for 15 seconds. After casting, all samples were kept sealed for 24 hours at a constant temperature of 23.0±1.0°C before they were demolded. The unsealed ring specimens were exposed to 50% relative humidity (RH) 24 hours after casting and were sealed on the top surface with aluminum tape to limit moisture loss to the outer circumference only (the bottom surface was sealed by the ring’s base support). Restrained shrinkage data was measured using Strain Smart\(^\circledR\) software and collected in 5 minute intervals.

Internal Relative Humidity Measurements

To measure change in the internal relative humidity of a sealed sample over time, specimens were cast in plastic containers which were demolded at an age of 12 hours. Approximately
10 g of the sample was crushed and placed in a glass container with a diameter of 1 inch and a length of 2 inches and sealed to prevent loss of moisture. The sealed glass container was kept in an environmental chamber so a constant temperature of 23.0±1.0°C could be maintained. A Digitron 2080R temperature and relative humidity meter was used to record relative humidity and temperature data inside the sealed container at 2 hour intervals for a duration of 7 days. The sensor was calibrated using saturated salt solutions with a known relative humidity in the range of 75-100% (ASTM E104-02).

**EXPERIMENTAL RESULTS**

The following section discusses the experimental results for both the sealed and unsealed specimens. The experimental results for the sealed system include internal relative humidity, unrestrained shrinkage, and restrained shrinkage. The measurements for the unsealed system include weight loss, unrestrained shrinkage, and restrained shrinkage.

**SEALED SYSTEM**

Saturated lightweight aggregates reduce the shrinkage of sealed cement paste. LWA contains water-filled pores that are larger than the capillary pores in the cement paste. When the paste begins to self-desiccate, the largest pores would empty first. However, the pores in the LWA are larger than the pores of the paste and water is transferred from the LWA to the pores in the paste. Figure 4 shows the measured change in internal relative humidity for seven days. As expected, a higher replacement volume of saturated LWA results in a higher internal relative humidity.

Figure 5 shows the unrestrained length change (i.e., free shrinkage) of each mixture. The data for the unrestrained length change is a combination of the first 24 hours of the corrugated tube procedure and the 28 day results determined from the prisms. The combination of the data was necessary to monitor the unrestrained length change from the time of set. As expected, the mixture with the largest shrinkage was the plain mixture. The mixture containing 7.3% LWA shows slightly different shrinkage but behaves very similar to the plain mixture. An initial expansion of approximately 200 με is measured at 24 hours for both the 14.3% and 25.3% replacement volumes. The mixture with 14.3% LWA reaches a peak of 200 με at 24 hours before it begins to shrink. The mixture with 24.3% LWA expands until 14 days, after which it shows an expansion of approximately 300 με.
Figure 6 shows the strain measured from the inner surface of the restrained ring (note a typical response is shown for one ring that reflects the behavior of the three samples tested). The plain mixture cracks after approximately 6 days. The time to cracking for the mixture with 7.3% LWA is nearly twice that of the plain mixture. Though this mixture showed a similar shrinkage when compared with the plain mixture, it should be noted that the elastic modulus would be expected to be lower in the LWA mixture, the relaxation may be expected to be higher, and the fracture toughness would be higher than the plain mortar. These factors may act together to increase the resistance of these materials to develop cracks at an early age.

After an initial expansion during the first 24 hours the mixture with 14.3% LWA begins to shrink. The mixture with 25.3% LWA also expands during the first 24 hours and then shrinks, but it appears to reach a length that is nearly in constant after two days. It should be noted that a slight expansion is experienced. This may be partially due to the heat produced by the hydrating cement and the water that is given from the LWA shortly after the paste sets.
Figure 4 RH measurements of sealed specimens

Figure 5 Free shrinkage measurements (zeroed at time of set) of sealed specimens
Figure 6 Restrained shrinkage measurements for sealed specimens

UNSEALED SYSTEM

In an unsealed specimen, in addition to self-desiccation, moisture is lost to the environment due to drying from the surface of the specimen. As a result, the total specimen shrinkage can be considered as the sum of self-desiccation and drying shrinkage. The presence of LWA in an unsealed specimen provides extra moisture that would be available for evaporation. As water evaporates from the surface of specimen, the moisture inside the LWA starts to be removed from the LWA filling in the smaller capillary pores of the cement paste thereby reducing shrinkage. Because shrinkage is reduced, the time of cracking can be extended in mixtures containing sufficient amounts of LWA.

Figure 7 shows the change in mass due to drying for the mixtures. The mass loss is largest for the mixtures with a larger replacement volume of LWA. It should be noted that the mixture containing more saturated LWA has more water that is available for evaporation. It can also be seen that the plain mixture and mixtures with low volumes of LWA have similar mass loss.

Figure 8 shows the unrestrained length change of each mixture exposed to drying. As expected, the plain mixture shows the most shrinkage in 28 days. It can also be seen that the mixtures with 7.3% LWA again performs similar to the plain mixture. The first 24 hours of the unsealed specimens is the same as the sealed specimens. After 24 hours the specimens were exposed to drying. The mixture containing 14.3% LWA shrinks to more than -400 με at 28 days. The mixture containing 25.3% LWA only shows shrinkage of -50 με at 28 days.

Figure 9 shows the strain measured from the restrained ring tests. It can be seen that the times of cracking are prolonged with increasing replacement volumes of LWA with a significant increase observed for the 25.3% replacement which is consistent with previous work\(^\text{11}\). It also can be noticed that not only are the times to cracking different, but the
magnitude of strains developed are different as well. Cracking is observed at much lower magnitude of strain due to the tensile strain capacity of the LWA mixtures.

Figure 7 Mass of water lost in unsealed free shrinkage specimens

Figure 8 Free shrinkage measurements (zeroed at time of set) of unsealed specimens
Several conclusions can be made from these preliminary results. An internal higher relative humidity is maintained for specimens with larger replacement volume of LWA. This would imply that the pores of the LWA are emptying before the pores of the hydrating cement paste. A small replacement volume of LWA may have negligible effects on reducing free shrinkage and shrinkage cracking. This is likely due to the low expansion of this mixture during the first 24 hours and can be seen in both sealed and unsealed conditions. This may be due to the fact that the LWA are spaced too far apart to supply water to all of the cement paste and pockets of self-desiccating paste may still exist. As expected a larger replacement volume of LWA produced better performing concrete. As the replacement volume was increased, the rate of shrinkage and absolute shrinkage were dramatically reduced. The mixture with 25.3% LWA was designed to eliminate self-desiccation. It can be seen in a sealed system this replacement volume virtually eliminated the effects of self-desiccation.

**CONCLUSIONS**

This paper has shown the influence of boundary conditions on the performance of self-curing concrete. The inclusion of a sufficient volume of saturated LWA can significantly reduce self-desiccation, reduce autogenous shrinkage and can delay the time to cracking or prevent cracking entirely. A summary of the general conclusion from this paper are:

**Sealed Specimens**
- Self-desiccation results in a reduction in the internal relative humidity of a low water to cement ratio paste. Specimens with a larger replacement volume of LWA maintained a higher internal humidity as expected.
• Specimens with a larger volume of LWA showed a reduction in rate of shrinkage and absolute shrinkage. This can be attributed to the ability of the aggregate to supply water to the hydrating paste which acts to reduce the effects of self desiccation and increases the internal relative humidity.
• Similar free shrinkage and cracking behavior was observed between a plain mixture and mixtures with low volumes of LWA replacement. This may be due to the fact that the LWA particles are spaced too far apart to effectively supply water to all the paste.

Unsealed Specimens
• A larger mass of water was lost for samples with an increasing volume replacement of LWA. This is consistent with these mixtures having a larger volume of initial water.
• The addition of LWA showed a reduction in the absolute shrinkage during first 28 days. This may be due to the initial reduction in self desiccation and the additional water that can complete hydration and temporarily replace the water that is lost to the environment.
• The time to cracking is prolonged for mixtures with an increasing replacement volume of LWA. This is likely due to the reduced shrinkage, reduced elastic modulus, increased relaxation, and increased fracture toughness.

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REFERENCES